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Survey of hybrid liquid desiccant air conditioning systems

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ABSTRACT

This paper reviews and surveys the available hybrid liquid-desiccant air-conditioning system technologies. These technologies are proposed as alternative to the traditional vapor-compression systems because of its advantages in removing air latent load, environment-friendly feature, ability to remove pollutants from the processed air, and ability to reduce electrical energy consumption. This paper first introduces the traditional air-conditioning system: vapor compression, vapor absorption, and evaporative cooling. In addition, the principles of liquid desiccants and liquid-desiccant dehumidification systems and the hybrid liquid-desiccant classifications are discussed. Next, combination of the liquid-desiccant systems with vapor compression, vapor absorption, and direct and indirect evaporative cooling units are outlined. Finally, conclusions and some important suggestions are presented based on the collected information.

Contents

1. Introduction

The two most common types of refrigeration systems are vapor-compression and vapor-absorption systems. In the vapor-compression system, an external source of shaft power is required to run the compressor. The vapor-compression cycle is the most widely used refrigeration cycle. In this cycle, vapor is compressed and condensed into liquid. The pressure is lowered to allow fluid to evaporate at low pressure. This refrigeration cycle requires additional external work for its operation. The processes that constitute the cycle are as follows: adiabatic compression, isothermal rejection of heat, adiabatic expansion, and isothermal addition of heat.

In recent years, many refrigeration vapor-compression systems have been introduced and developed to increase the efficiency of power distribution and to utilize industrial waste heat and renewable clean energy. Zubair et al. [1] applied the automatic hot-gas bypass technique to reduce the capacity of refrigeration and air-conditioning systems when operating at

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partial load. Zubair [2] demonstrated the advantages of add-on sub-cooler systems to improve the performance of refrigeration and air-conditioning systems. Chen and Jianlin [3] obtained better performance of a new refrigeration cycle for binary non-azeotropic mixed (R22/R134a). The performance of the new mixture in this new cycle was close to that obtained with R22. The mixed coefficient of performance (COP) of the system can be improved within the range from 8% to 9% of the conventional refrigeration cycle. Wang et al. [4] performed a thermodynamic and economic analysis of a novel compressed-air energy-storage refrigeration system; the system was a combination of a gas refrigeration cycle and a vapor-compression refrigeration cycle. Liu et al. [5] performed a thermodynamic analysis of the actual air cycle refrigeration. The results of their study showed that the pressure ratio, working temperature, and isentropic efficiency of the rotors were effective in the actual cycle performance. Toublanc and Clausse [6] proposed a novel Carnot-type cycle to achieve high performance for trans-critical and sub-critical applications. The COP of the cycle was higher by 4–70% than the conventional cycle.

The vapor-absorption systems are similar to the vapor-compression systems except for the pressure employed at each stage [7]. The absorption systems use heat energy to produce refrigeration; water is used as refrigerant, and lithium bromide is generally used as the absorber of the refrigerant [8]. Ammonia water and water lithium bromide are often used in absorption refrigeration systems, whereas ammonia water is used in condensers [9]. The required heat source temperature for this system is approximately 300 °F. Commercially, two types of absorption systems are available: the single and the double effect. The main purpose in increasing the effect cycle is to increase the system performance at high heat source [10].

Evaporative cooling is one alternative to mechanical vapor compression for air-conditioning applications. Evaporative cooling system requires only a quarter of the electric power than the mechanical vapor-compression uses for air conditioning [11]. Low energy- consuming devices were used in [12–15] for various industrial, agricultural, and residential cooling and air-conditioning applications to reduce greenhouse-gas emissions. As reported in [16], only sensible load can be handled by an evaporative cooling system, and the conventional evaporative cooling system is suitable for dry and temperate climates.

The two common types of evaporative cooling system are the direct and indirect systems [17,18], where the effectiveness of the direct evaporative cooling system is approximately 70–95% in terms of temperature. The direct evaporative cooling system adds moisture to the cooled air, whereas the indirect evaporative cooling system provides only sensible cooling to the processed air with no moisture added. Therefore, the indirect evaporative system is more attractive than the direct evaporative system. However, its cooling effectiveness is generally low, which is approximately from 40% to 60% [19].

2. Principle of liquid desiccants

The dehumidifier and regenerator are the main components of a liquid-desiccant dehumidification system. The most common technology today for the dehumidifier and regenerator is the packed bed. However, packed beds must work under high desiccant-flow rates to achieve good dehumidification without internal cooling [20]. The main role of the desiccant is to attract water vapor from air; thus, it can be classified as both solid and liquid desiccant. Several types of solid materials can hold off water vapor, e.g., silica, polymers, zeolites, alumina, hydratable salts, and mixtures. Other available liquid desiccants are calcium chloride, lithium chloride, lithium bromide, tri-ethylene glycol, and a mixture of 50% calcium chloride and 50% lithium chloride. These liquid desiccants have common general properties, but their requirements cannot be fully addressed by any single desiccant. These requirements include low vapor pressure, low crystallization point, high density, low viscosity, low regeneration temperature, and low cost. Several works have been done to investigate the characteristics of a single and the mixture of two liquid desiccants.

Liquid desiccants can be regenerated at low temperature, from approximately 50–80 °C [21]. Thus, the regeneration process could be driven by heat sources with a relatively low temperature of approximately 70 °C, such as solar energy, waste heat, and geothermal power. Hassan and Salah [22] proposed a desiccant with a mixture of 50% weight of water calcium chloride and 20% calcium nitrate. They studied the physical properties of the mixture, such as viscosity, vapor pressure, density, and heat, and the mass transfer process. The results of their study showed a significant increase in vapor pressure of approximately 14.7, 20.6, 34.4, and 47.3 mm Hg at 30, 40, 50, and 60 °C, respectively. Xiu-Wei Li et al. [23] proposed a novel method that mixed lithium calcium chloride and lithium chloride. The experimental results showed that the dehumidification effect of the mixture was 20% more than the lithium chloride solution alone.

3. Principle of liquid-desiccant dehumidification and regeneration process

Air is dehumidified when it comes in contact with strong liquid or solid desiccants; subsequently, to provide sensible cooling to the dehumidified air, traditional vapor compression, vapor absorption, and direct or indirect evaporative cooler units are used, and the dehumidified air is sent to the conditioned space. When the solution is weakened by absorption of moisture, it is sent directly to the regeneration process to release the moisture using external heat resources. This process is called "reactivating" the desiccant [24].

The simplest liquid-desiccant system configuration, shown in Fig. 1, consists of a conditioner, regenerator, a heat exchanger to heat the solution, and another heat exchanger to cool the solution. The solution attracts moisture from the air in the conditioner, which weakens the solution. The weak solution is sent through the heat exchanger for heating and then sprayed into the regenerator. In the regenerator, the air carries away the water vapor from the solution. After this process, the solution is sent to the conditioner across the heat exchanger for cooling.

Liquid-desiccant dehumidification often requires two desiccant air-contact devices: absorbers and regenerators. A liquid-desiccant absorber/regenerator system has three configurations: packed tower, spry chamber, and spry coil arrangement [25]. Models for heat and mass transfer in the packed configuration

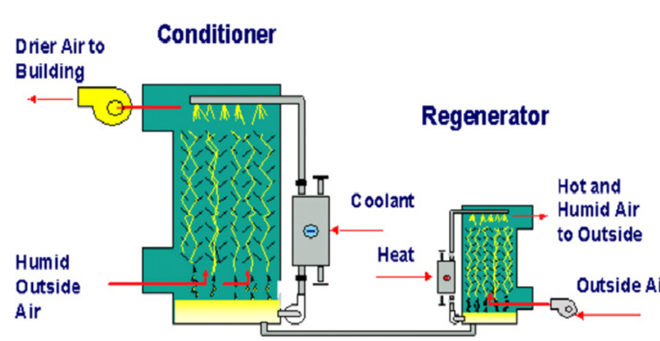

Fig. 1. Liquid desiccant system.

have received more attention; many researchers [26–29] studied the adiabatic counter-flow configuration.

4. Hybrid liquid desiccant systems and their classifications

The combination of the ability of the liquid-desiccant dehumidification process in removing latent load and the ability of the cooling unit to meet sensible cooling load is defined as hybrid liquid-desiccant air-conditioning system. The main classification of the hybrid liquid-desiccant cooling system is based on the cooling units used in the reduction of the dehumidified air temperature. The dehumidifier subsystem needs to remove only enough moisture to satisfy the building needs by reducing the size of the dehumidifier and lowering the required regeneration temperature needed by the desiccant cooling system from (70–80) °C to (50–60) °C [30]. In this review, the hybrid desiccant cooling system consists of three main components, namely, the dehumidifier (liquid-desiccant material), the regenerator, and the cooling unit (Fig. 2).

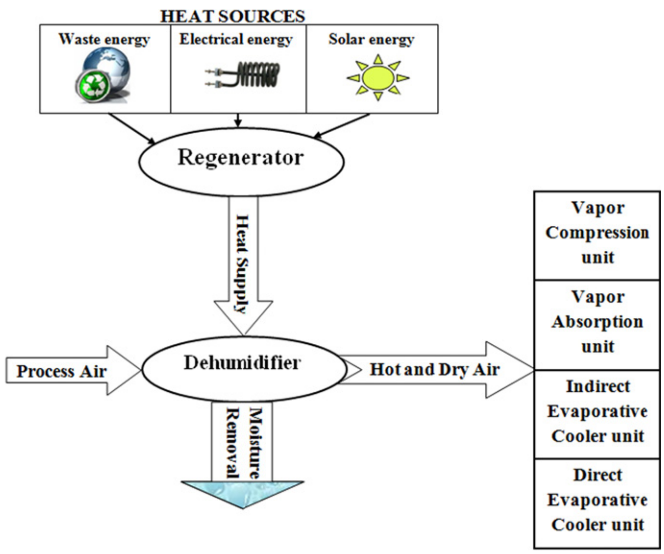

Fig. 2. Classifications of hybrid liquid desiccant air conditioning systems and their components.

4.1. Hybrid liquid desiccant based vapor compression system

Al-Farayedhi et al. [31] combined a 5-ton-capacity vapor-compression unit with a packed dehumidifier and regenerator. A gauze-type structure was used as packing towers with the following dimensions: height = 2.6 m; diameter = 50 cm; and thickness = 0.5 cm. Calcium chloride was used as liquid desiccant to dehumidify the air inside the dehumidifier. The results showed that the hybrid cooling system provided higher COP than the conventional system. The COPs of the hybrid desiccant system for different modes of regeneration process were as follows: desiccant heating = 1.164; air heating = 1.616, and desiccant and air heating = 1.4221; the COP of the vapor compression unit was 0.989. Dai et al. [32] established a hybrid air-conditioning system consisting of a vapor-compression unit, desiccant dehumidification, and evaporative cooling, as shown in Fig. 3. The desiccant dehumidification unit consisted of packing honeycomb paper. The COP of the system increased by approximately 23.1% compared with the COP of the conventional vapor system when the dehumidification

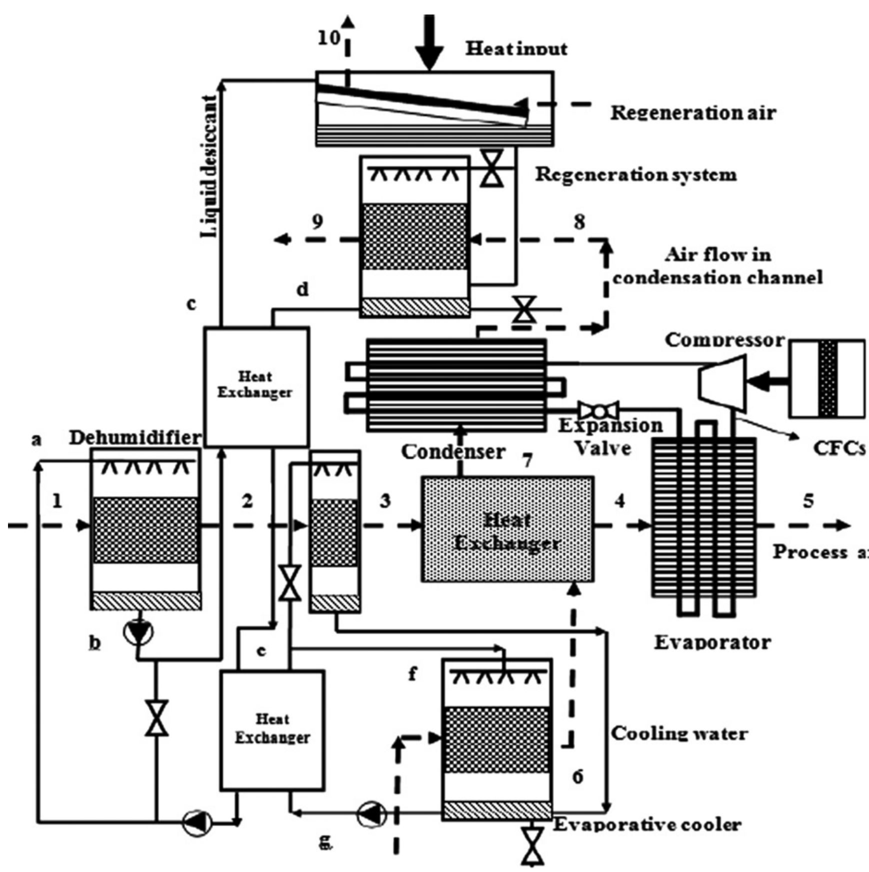

Fig. 3. Schematic of the hybrid cooling system [32].

section was considered. It increased by 15.3% when the dehumidification and evaporative sections were taken into account. Arnas and McQueen [33] combined a split package air-conditioning system with a desiccant air-conditioning unit to optimize the system and its components. The dehumidification unit consisted of a cross flow, flat plate heat exchanger, and a vapor barrier. Calcium chloride was used as the solution in the dehumidifier. Zhang et al. [34,35] integrated the heat-pump system into a liquid-desiccant dehumidification unit; the system provided both cooling and dehumidification in the summer mode and heating and humidification in the winter mode. Two major units represented the system: the sensible heat and the latent heat removal units, as shown in Fig. 4. Two refrigerant cycles corresponded to the two heat pumps in the hybrid air-conditioning system: one was used to deal with the sensible return air, whereas the other dealt with pre-cooling the liquid desiccant on the dehumidification side and re-heating the liquid desiccant on the return side. The figure shows the psychometric of the process (a) in winter and (b) in summer. The results showed that the COP was 30% to 40% higher than that of the heat pump integrated with an electric heater. Alsaid [36] called the integrated liquid-desiccant dehumidification unit with vapor-compression system as a hybrid desiccant-assisted air conditioner. Lithium chloride was used as the working solution in the dehumidifier. The system offered a total cooling capacity of approximately 6.15 kW using a 2.6 kW vapor-compression system with R-134a as refrigerant (Fig. 5). Bergero and Chiari [37] examined the performance of an air dehumidification system integrated with a vapor-compression inverse cycle. As shown in Fig. 6, air is dehumidified in the air-solution membrane contractor and cooled by the vapor-compression cycle. Lithium chloride (as a solution) was cooled by the vapor-compression unit and regenerated in another membrane. Bergero and Chiari [38] studied the steady state behavior of the system mentioned in [37]

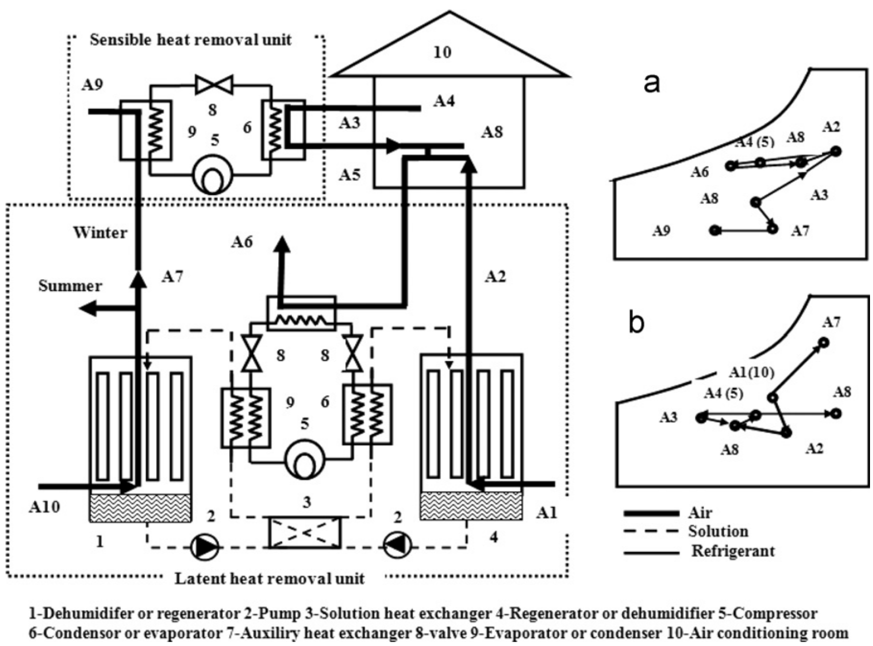

Fig. 4. Schematic diagram of hybrid air conditioning with Psychometric chart for (a) winter and (b) summer [34].

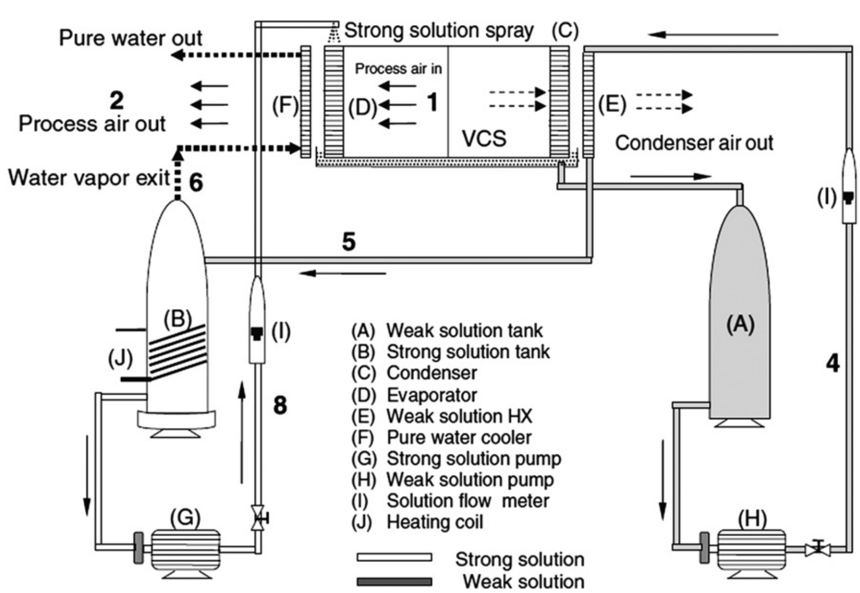

Fig.5. Schematic diagram of the multi-purpose integrated HDAC system [36].

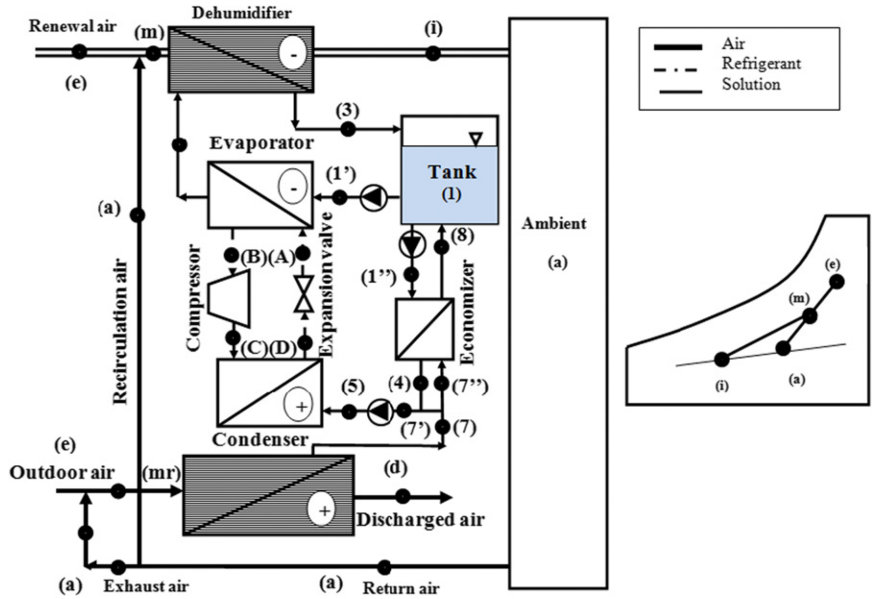

Fig. 6. Layout of hybrid air conditioning system [37].

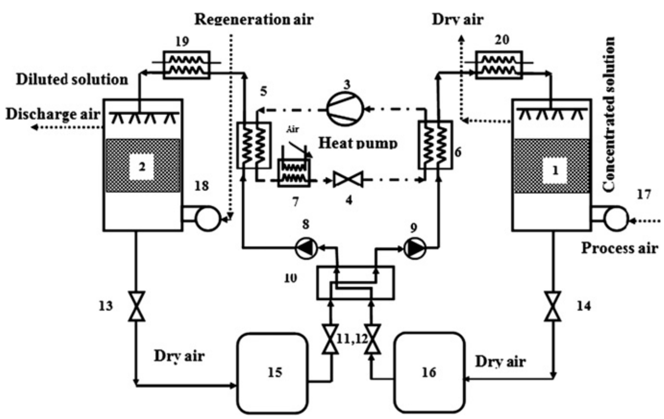

Fig. 7. Schematic diagram of liquid desiccant heat pump system [41].

under different significant climatic parameters. The results showed a 60% energy savings at high latent-heat load compared with a traditional direct expansion air-conditioning system. Ma et al. [39] analyzed the performance of a hybrid air-conditioning system using a vapor-compression heat pump to cool the air in the evaporating end and the liquid-desiccant dehumidification system to treat the latent heat. The results showed that the performance of the system at 30% latent heat was 44.5% more than the conventional vapor compression. Seiichi et al. [40] conducted a performance evaluation test of a hybrid liquid-desiccant air-conditioning system consisting of a conventional liquid-desiccant system and a vapor-compression heat pump. In this system, lithium chloride was used as the solution in the dehumidification unit. The results showed that the COP of the system was 2.71, which can be improved by improving the compressor isentropic efficiency. Xiaofeng et al. [41] studied the capacity matching of a hybrid liquid-desiccant air-conditioning system consisting of liquid-desiccant dehumidification with lithium chloride as the solution and a heat-pump system with double condensers used for cooling the air and another used for the cooled solution, as shown in Fig. 7. The results showed that the system with a double condenser is a feasible configuration to achieve capacity matching. Yadav [42] investigated the effect of the operating parameters on the performance of a hybrid solar air-conditioning system. The system consists of liquid-desiccant cycles and conventional vapor compression. Lithium bromide was used as the solution in the liquid-desiccant cycle, and R-11 was used as refrigerant in the V-C system. Fig. 8 shows the circulation of the working fluid and the psychometric chart of the hybrid system. The results showed that the system is more promising under high latent-heat load. Kinsara et al. [43] proposed an energy-efficient system to reduce the energy consumption of an air-conditioning system; the proposed system consisted of a liquid-desiccant cycle and a heat-pump unit. Calcium chloride was used as the solution in the desiccant cycle. Fig. 9 shows this type of air-conditioning system. The results showed that the energy-efficient system consumed approximately one-third of the energy used by a conventional system at an air humidity ratio of 0.015 kg/kg, an ambient temperature of 40 °C, and SHR of 0.9. Ania et al. [44] designed, fabricated, and tested a hybrid system consisting of two sub-systems: a liquid-desiccant sub-system that used lithium chloride as solution with a flat plate collector and a vapor-compression sub-system. The optimum performance of the system was tested under various dehumidifier packing heights. Fig. 10 shows the effect of the dehumidifier packing height on the system COP. A dehumidifier height of 1000 mm was most suitable in improving the COP by 17.9–48.5%. Studak and Peterson [45] used hybrid desiccant air conditioning to investigate the best liquid desiccant among lithium bromide, lithium chloride, triethylene glycol, and calcium chloride; the liquid desiccant was circulated between the evaporator and the condenser of the vapor-compression air conditioning, as shown in Fig. 11. The results showed that calcium chloride is the best liquid desiccant.

The amount of heat from the condenser in a hybrid liquid-desiccant system is often more than the heat needed in the desiccant regeneration process. Zhang et al. [46] used two different methods to remove the extra heat. In the first method, they used a water-cooled assistant condenser; in the second method, they added an air-cooled assistant condenser. Fig. 12 shows the different types of heat-pump-driven liquid-desiccant dehumidification. The COP of the system with the water-cooled condenser was approximately 35% higher than that of the basic system. Shaji et al. [47] analyzed the heat and mass transfer of the dehumidifier and regenerator in a hybrid liquid-desiccant system; the analysis was performed in a counter-flow configuration, as shown in Fig. 13, under varying parameters such as the ratio of solution to the air mass flow rates and the temperature and

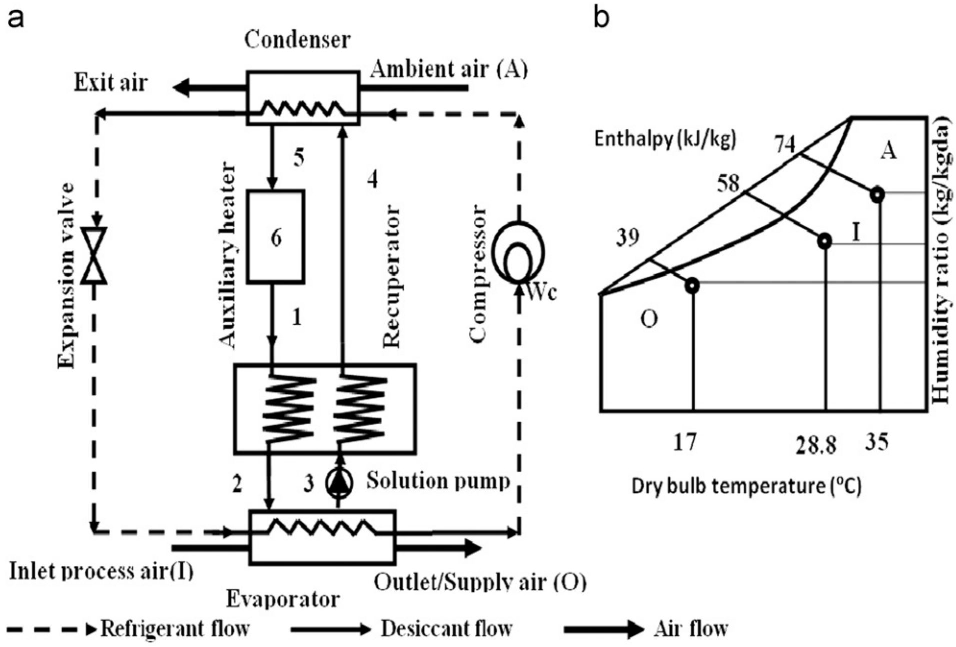

Fig. 8. V-C liquid desiccant hybrid solar space conditioning system [42].

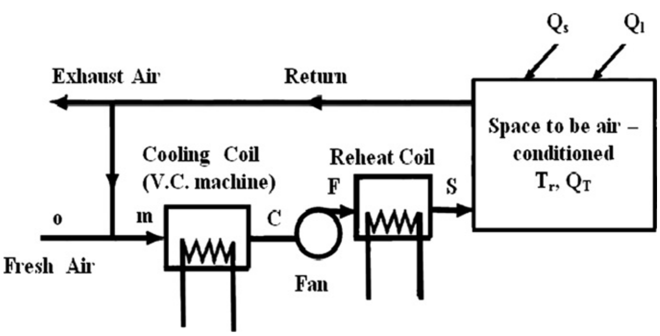

Fig. 9. Typical air-conditioning system [43].

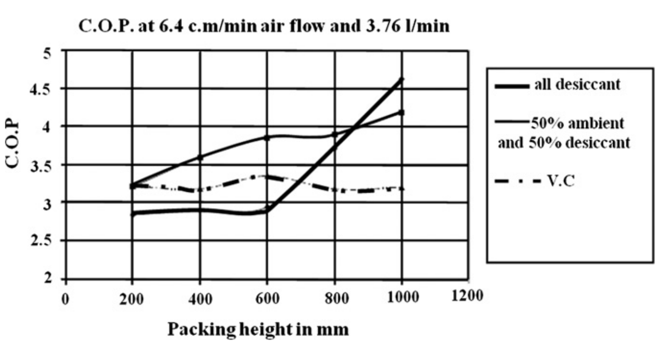

Fig. 10. The impact of packing height of absorber on COP [44].

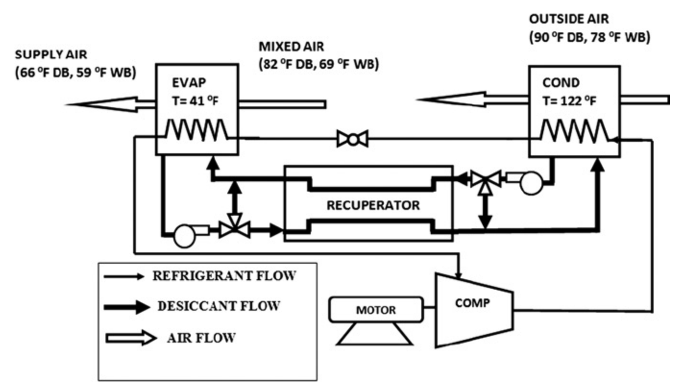

Fig. 11. The proposed hybrid vapors compression/liquid desiccant air conditioning [45].

specific humidity of air. Oberg and Goswami [48] simulated the performance of a solar hybrid liquid-desiccant system cooling for ventilation air pre-conditioning. The liquid-desiccant cycle used a packed bed at high flow rates, using tri-ethylene glycol as solution. A solar-energy subsystem was used to regenerate the weak solution in the regenerator. The results showed an 80% reduction in electrical energy consumption compared with that using a conventional vapor-compression system. Lazzarin, Lazzarin and Castellotti [49] compared the energy savings of a numerical model with that of a traditional mechanical dehumidifier. The weak desiccant solution was regenerated using the thermal energy supplied from a primary heat-pump condenser, whereas air regeneration was used as secondary heat-pump condenser. The results of the study showed that the primary energy consumption for July can be lowered from 26% to 63%. Yutong et al. [50] used a transient simulation model and the Energy Plus to study the energy performance and economic feasibility of a solar hybrid liquid-desiccant dehumidification system with conventional vapor-compression unit in Hong Kong. The ambient humid air entered the supply air duct and passed through the dehumidifier; after exiting the dehumidifier, the hot and dry air was then cooled by the cooling coil. The weak liquid desiccant was regenerated in the solar collector regenerator. When solar radiation was not sufficient to regenerate the solution, an electric auxiliary heater was used to increase the weak solution temperature. The results showed that the capacity of the hybrid system can reduce the capacity of the original conventional air-conditioning system from 28 kW, which costs HK$ 20,000.00 to 19 kW, which costs HK$ 12,000.00.

4.2. Hybrid liquid-desiccant-based vapor-absorption system

Ahmed et al. [51] simulated the COP of a hybrid open cycle that consisted of a vapor-absorption system and a liquid-desiccant system using lithium bromide as the working fluid for the

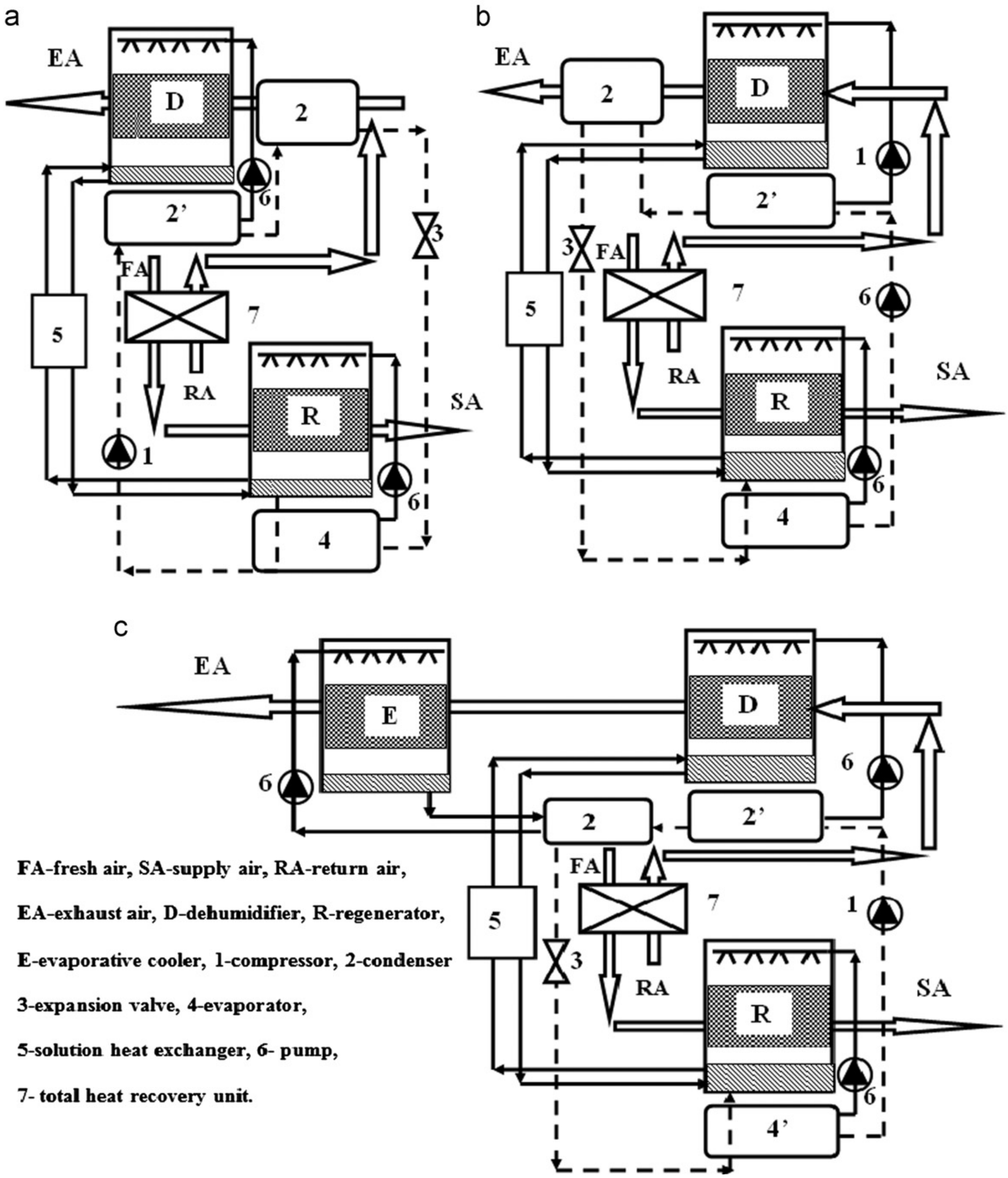

Fig. 12. Different HPLD systems: (a, b) with an air cooled assistant condenser and (c) with a water cooled assistant condenser [46].

absorption and dehumidification process. Fig. 14 shows that air is dehumidified in the absorber and cooled in the evaporator. The system achieved a COP of approximately 50% more than the COP of the conventional absorption system. El-Shafei et al. [52] studied the effect of design parameters and operating conditions of an open absorption cooling cycle. The cycle consisted of a solar-powered regenerator with calcium chloride as a desiccant, as shown in Fig. 15. The weak absorbent solution was heated directly in the solar collector and passed through a liquid column.

4.3. Summary of the vapor and absorption systems

Table 1 summarizes the main details of the hybrid liquid-desiccant air-conditioning technologies and their performances, which could help researchers in selecting the best technology for specific applications.

4.4. Suggestions of combining the vapor-compression systems

Based on previous studies, the following guidelines are suggested to produce a better combination of liquid-desiccant dehumidification and vapor-compression system in constructing a hybrid air-conditioning system:

1) Choose the best liquid desiccant to obtain good dehumidification (better heat and mass transfer process) at lower driving temperature. Based on previous studies, lithium chloride was used more often than the other liquid desiccants.

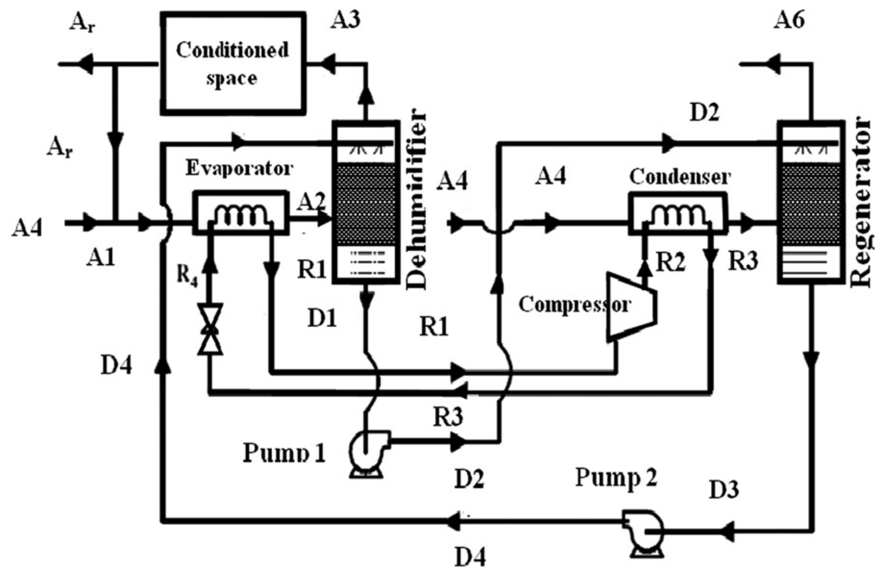

Fig. 13. Block diagram of the proposed system [47].

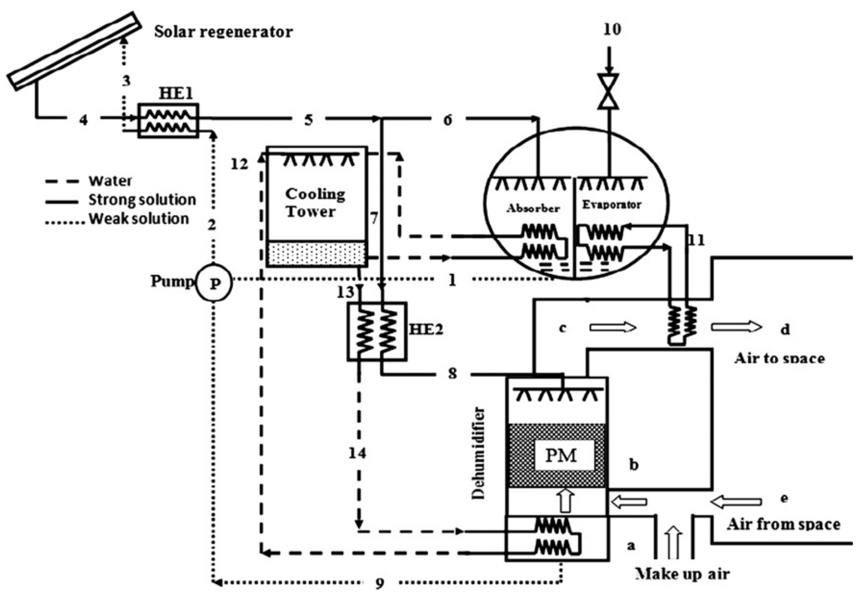

Fig. 14. Hybrid vapor-absorption and liquid-desiccant cycle [51].

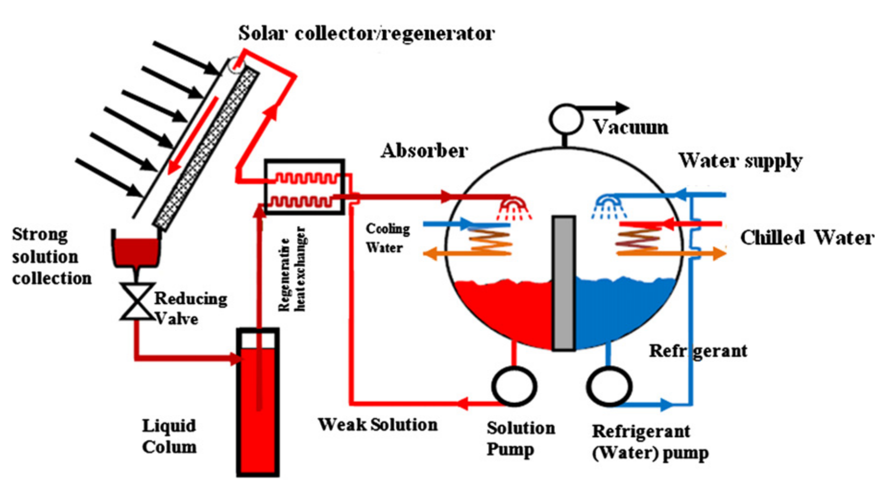

Fig. 15. Schematic of the solar-powered open absorption cooling system [52].

Table 1
Summary of the systems.

References	Liquid desiccant type	Regeneration process type	COP and capacity
[31]	$CaCl_2$	10 KW electrical heater	1.164–1.616
[32]		Solar energy	23.1 more than COP_{vcs}
[33]		VCS	
[34]	LiCL	HP	30–40% higher than COP_{HP}
[35]	LiCL	VCS	
[36]	LiCL	VCS	6.15 KW
[37]	LiCL	VCS	50% energy saving
[38]	LiCL	VCS	60% energy saving
[39]	LiBr	VCS	44.5–73.8% more than COP_{vcs}
[40]	LiCL	VCS	2.71
[41]	LiCL	HP	1.33–1.35
[42]	LiBr	VCS	53–80% energy saving
[43]	$CaCl_2$	VCS	1/3 energy saving
[44]	LiCL	Solar energy	increase 19.9–48.5%
[45]	LiBr, LiCL, $CaCl_2$, TEG	VCS	
[46]		VCS	35% more than basic system
[47]		VCS	
[48]	TEG	Solar energy	
[49]		HP	26–63% energy lowering
[50]	LiBr	Solar energy+auxiliary heater	9 KW energy lowering
[51]	LiBr	Solar energy	COP 50% more than COP_{Abs}
[52]	$CaCl_2$	Solar energy	Max COP=0.4

VCS=vapour compression system, HP=heat pump, Abs=absorption system.

2) Choose the best liquid-desiccant dehumidifier/regenerator configuration. Many of the previous studies conducted experiments on the counter-flow configuration because it performed better than the parallel- and cross-flow configurations.
3) Investigate the different regeneration modes such as solar energy and waste energy.
4) Consider using a low-cost solar collector when the hybrid system uses solar energy to regenerate the desiccant.
5) Choose carefully the vapor-compression unit according to the climate conditions.

4.5. Hybrid liquid desiccant and direct evaporative cooler

Al-Sulaiman et al. [53] analyzed the performance of a liquid-desiccant system with two-stage evaporative coolers and used the reverse osmosis (RO) process to regenerate the weak solution. The main components of the RO system were a packed-bed dehumidifier and a regenerator with a diameter of 50 cm. The system consists of two stages from the dehumidifier and evaporative coolers and used $CaCl_2$ as liquid desiccant. The COP of the cooling system was defined as the cooling effect of the mass rate of water evaporated in the system divided by the amount of energy supplied to the system. Fig. 16 shows the system process on a psychometric chart. Gandhidasan [54] predicted that the amount of heat removed from the liquid-desiccant system operating on ventilation mode in terms of known initial parameters through a simplified vapor pressure is correlated to the effectiveness of the dehumidification and heat exchanger. His proposed cooling system worked at atmospheric pressure condition, as shown in Fig. 17. Calcium chloride was used as liquid desiccant, which was distributed in the dehumidifier, and the processed air was then cooled using the evaporative cooler. As reported in [55]

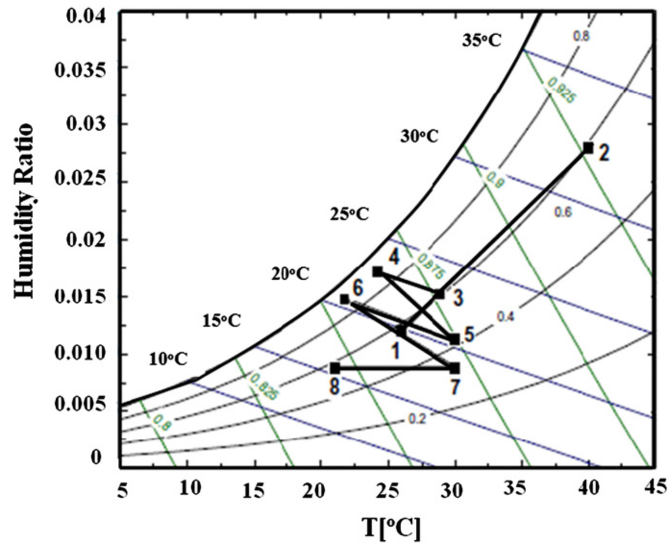

Fig. 16. Processes on the psychometric chart [53].

and [56], a dew-point evaporative cooling system was used to supply the outlet air temperature below the ambient wet-bulb temperature. Yin et al. [57] used experimental test to investigate the effects of heating temperature, desiccant solution temperature, desiccant solution concentration, air temperature, and air humidity on the evaporation rate of the dehumidifier and regenerator in the liquid-desiccant cooling system. The system had a packed-tower dehumidifier and regenerator with the dimensions of $(100 \times 60 \times 45)\,cm^3$ and 70 cm diameter × 80 cm high, respectively. The results showed that the mean mass transfer coefficient of the packing regenerator was 4 g/m^2 s.

Riangvilaikul and Kumar [58] constructed and tested a novel dew-point evaporative cooling system for sensible cooling; the objective of the experiment was to reduce the temperature of air leaving the dehumidifier without change in the moisture, as shown in Fig. 18. The system consisted of the air pre-conditioning unit dew-point evaporative cooling system. This unit was equipped with 1.5 kW pre-heater and re-heater and 5 kW water boiler systems. This system provided good performance under various operating conditions (humid and dry climate), where the dew-point and wet-bulb effectiveness ranged between (0.58 to 0.84) and (0.9 to 1.14), respectively. In the hot and dry climate, this system can provide comfortable condition at 45 °C inlet temperature and 11.2 g/kg humidity ratio. Gupta and Gandhidasan [59] designed and analyzed a 3-ton open-cycle solar air-conditioning system suitable for hot and humid climate. The system depended on the dehumidification of air using calcium chloride as the liquid desiccant, followed by adiabatic evaporative cooling by the cooling unit. One of the major advantages of the system was that the required temperature of 60–75 °C for regeneration of the absorbent solution can be easily obtained using a simple device—solar collector-cum-regenerator. Armando et al. [60] modeled a new liquid-desiccant system that used a needle impeller rotor, an evaporator, and an absorber. The cycle has no indoor air circulation; air moved though the needle impeller fans mounted on a shaft where the flexible impeller was installed by modeling a chimney sweep brush consisting of six rings, each having 2800 one-millimeter-thick nylon fibers. Ambient air entered the system and went to the absorber, where its water content was reduced, and the temperature was increased. The objectives of the system were to apply several operating conditions and to compete with the conventional system, as shown in Fig. 19. Alizadeh [61] used polymer heat exchanger (PPHE) for dehumidification by indirect

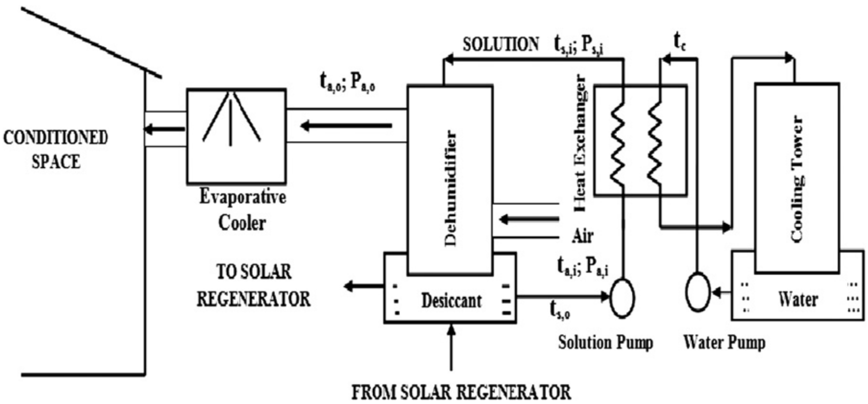

Fig. 17. Schematic of the liquid desiccant space cooling system [54].

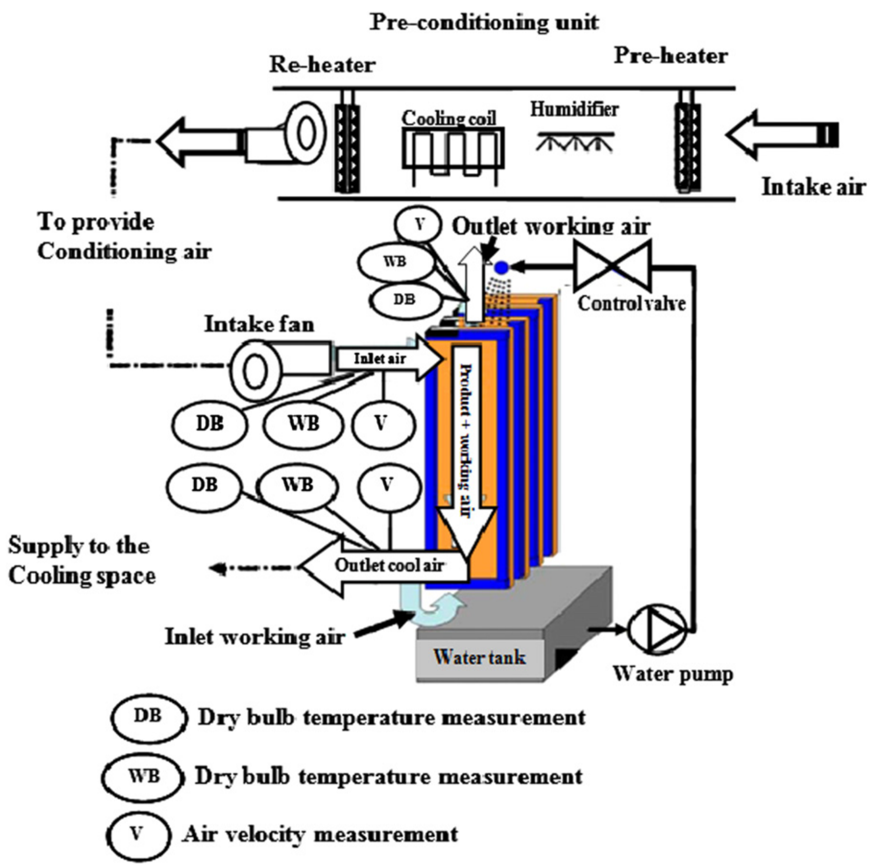

Fig. 18. Schematic drawing of experimental set up [58].

evaporative cooling, and a cooling pad was used as the direct evaporative cooler for the dry air leaving the PPHE. Eliminators were used at the outlet of the absorber unit, and the regenerator was used to prevent carryover. The system casing was made from fiberglass materials with dimensions of $(1.3 \times 1.5 \times 1.8)$ m. Two sumps and pumps at the bottom of the casing circulated the water and the solution using six spry nozzles fixed on the horizontal header tubes.

4.6. Hybrid liquid desiccant and indirect evaporative cooler

Katejanekarn et al. [62,63] used a heat exchanger to cool the dehumidified air, instead of evaporative cooling, to maintain air dryness. Solar panels were used in the regeneration process, and the system comprised two air loops (air processed in the dehumidifier and air regenerated in the regenerator) and two liquids loops (liquid desiccant in the dehumidifier/regenerator and water in the cooling tower unit), as shown in Fig. 20. The system reduced the temperature of the delivered air by approximately 1.2 °C, whereas the humidity ratio was reduced by 0.004 kg_w/kg_{da}, equivalent to an 11.1% relative humidity reduction. Kessling et al. [64] developed and tested a new dehumidifier that used aqueous salt solution ($LiCl–H_2O$). The system was designed to be driven by low-temperature heat ($T < 80$ °C) instead of electricity and consisted of a dehumidifier

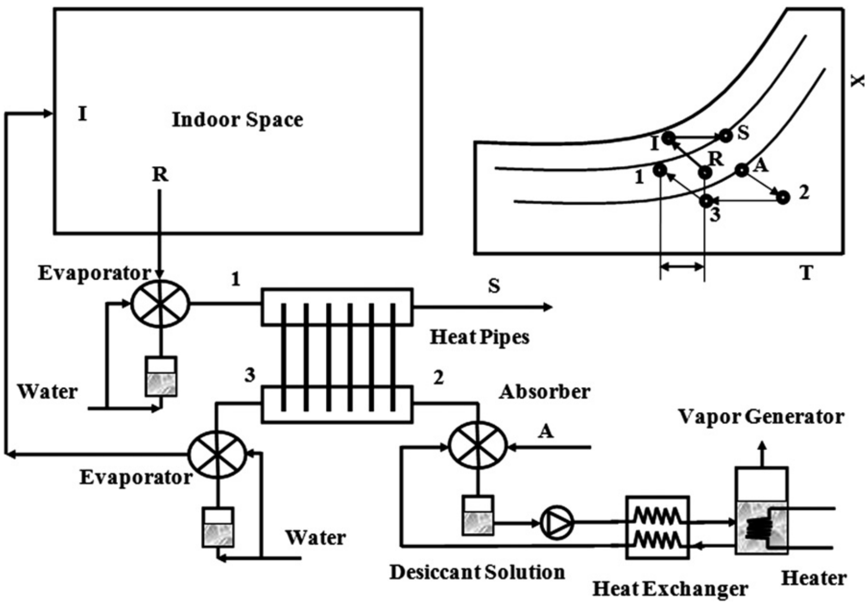

Fig. 19. Desiccant air conditioning cycle and air evolution in temperature (T)-water content (X) graph [61].

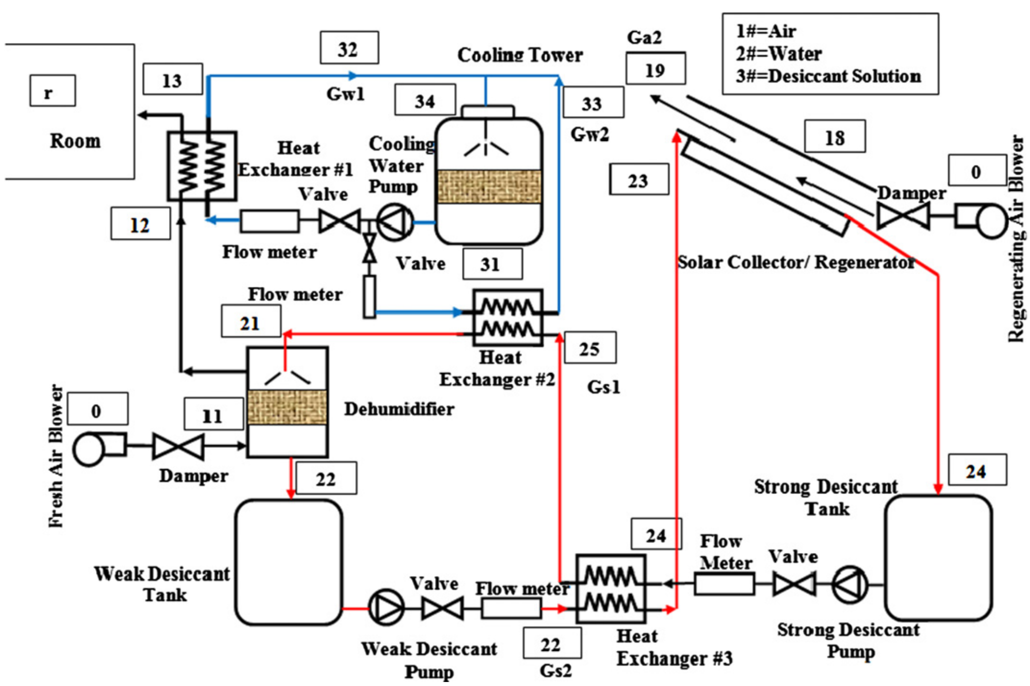

Fig. 20. Schematic of the solar regenerated liquid desiccant system [62].

and an indirect evaporative cooler. An experimental and theoretical model was investigated in [65] to predict the performance of a solar-powered liquid-desiccant cooling system for greenhouses. The system consisted of a dehumidifier, regenerator, and direct evaporative pad. The results showed that the desiccant system lowered the average daily maximum temperature in the hot season by 5.5–7.5 °C compared with the conventional evaporative cooling. Saman and Alizadeh [66] proposed a new type of liquid-desiccant dehumidifier and indirect evaporative cooler, which consisted of solution/air and water/air passages. In the solution/air passage, primary air was sprayed by liquid-desiccant solution, whereas in the water/air passage, secondary air was evaporatively cooled by water spray. The results showed that the proposed dehumidifier did not offset both the latent and sensible loads of the primary air; therefore, more dehumidification/indirect evaporative cooling stages are generally required to meet the sensible and latent loads in a typical comfortable application. Jason and Eric [67] proposed a liquid-desiccant air conditioner consisting of two stages; each stage was a mound of channel pairs. In the first stage, a liquid-desiccant film, which lined the processed-air channels, attracted moisture from the air through a porous hydrophobic membrane. An evaporating water film wetted the surface of the exhaust channels to cool the desiccant and lower the outlet humidity by transferring the enthalpy of vaporization from the liquid desiccant into the exhaust airstream. The second stage was a counter-flow indirect evaporative cooler that siphoned off and used a portion of the cool dry air exiting the second stage as the evaporative sink.

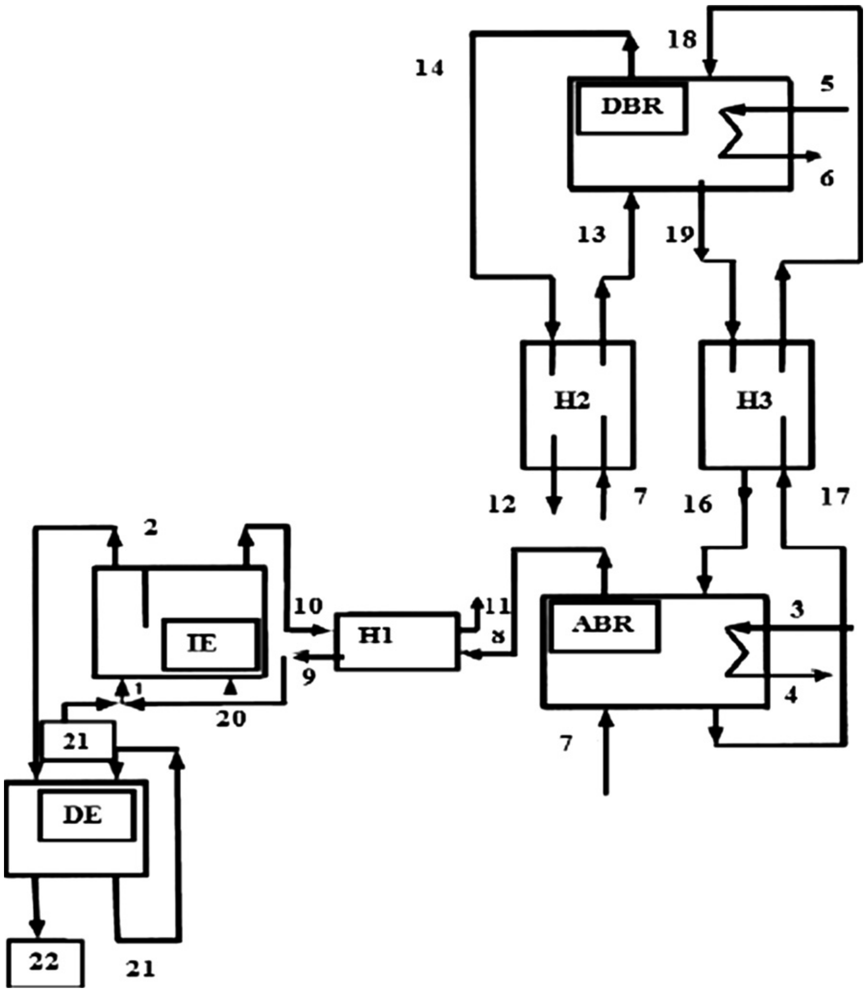

Fig. 21. Schematic description of the operation of the proposed air-conditioning cycle [68].

4.7. Hybrid liquid desiccant and indirect/direct evaporative cooler

This type of systems consists of four major components: absorber, regenerator, and indirect and direct evaporative coolers. A computer simulation was used by Tashtoush et al. [68] to investigate the performance of an open absorption system. Ambient air that entered the absorber at state 7 was brought into contact with a concentrated absorbent solution. The dehumidified air that left the absorber at state 8 was drawn through the first heat exchanger into IEC. Humid air left the evaporative cooler for ambient environment at state 10, and then it passed through heat exchanger H1. Further cooling was provided by the DEC at states 2 and 22, as shown in Fig. 21. The purpose of the solution–solution heat exchanger H3 was to pre-heat the weak solution and pre-cool the strong solution. The results of the simulation showed that the combined cycle was better by 20% than either the direct or indirect cooling cycle. Tu et al. [69] proposed and simulated a novel energy-efficient air-conditioning system. The system consisted of two packed columns: indirect and direct evaporative coolers, as shown in Fig. 22. The air was first dehumidified in the absorber and then sensibly cooled in the indirect and direct evaporative coolers. The weak solution was first pre-heated by the solution–solution heat exchanger (HE2) to point 2 after it left the dehumidifier at point 1 and later heated in the heater to point 3 before being re-concentrated in the regenerator. Tu et al. [70] compared the performance of two novel configurations of liquid-desiccant systems. The first configuration type (A) was the same system used in [69], and the second configuration type (B) was a modification of the first configuration type (A). Fig. 23 shows the simple modification of type (A) to type (B). The secondary air outlet from the indirect evaporative cooler was connected directly to the regenerator heat-exchanger (HE1) to regenerate the solution. The results of the simulation showed that the type (A) configuration showed better performance under lower absolute humidity of ambient air. By contrast, the type (B) configuration was superior when the supply air humidity ratio and temperature were required to be relatively low. Fig. 24 shows the simulation results on the psychometric chart for several important state points of the air and solution in configurations (A) and (B).

5. Conclusions

This review has demonstrated that liquid-desiccant dehumidification is a simple technology that can be improved by combining the conventional vapor-compression, vapor-absorption, and evaporative cooling technologies. One of the important advantages of liquid desiccant is that it can remove the latent heat of the processed air and regenerate it with low temperature using free energy such as solar and waste energy.

In hot and humid regions, application of the liquid-desiccant system combined with the conventional compression unit minimizes electric power consumption of VCS and its size. The reason lies in the dehumidification unit that removes the air-moisture content. From the extensive review of recent literature, the COP

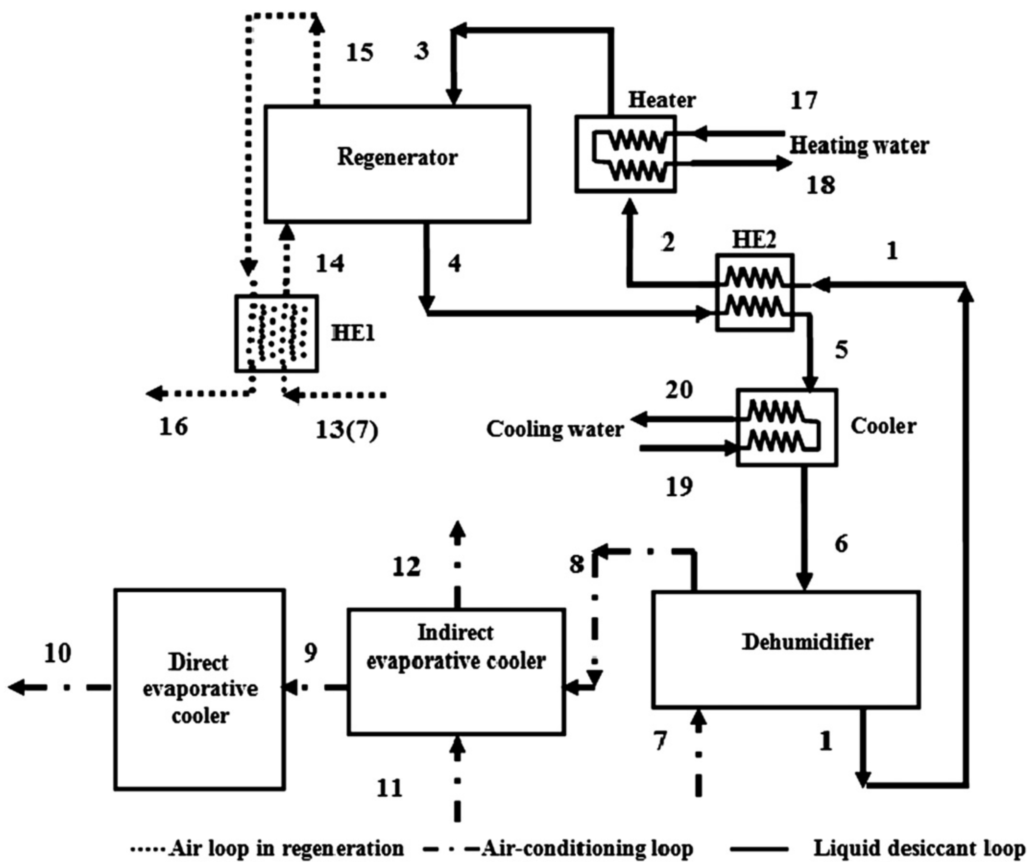

Fig. 22. Description for the proposed liquid desiccant air-conditioning system [69].

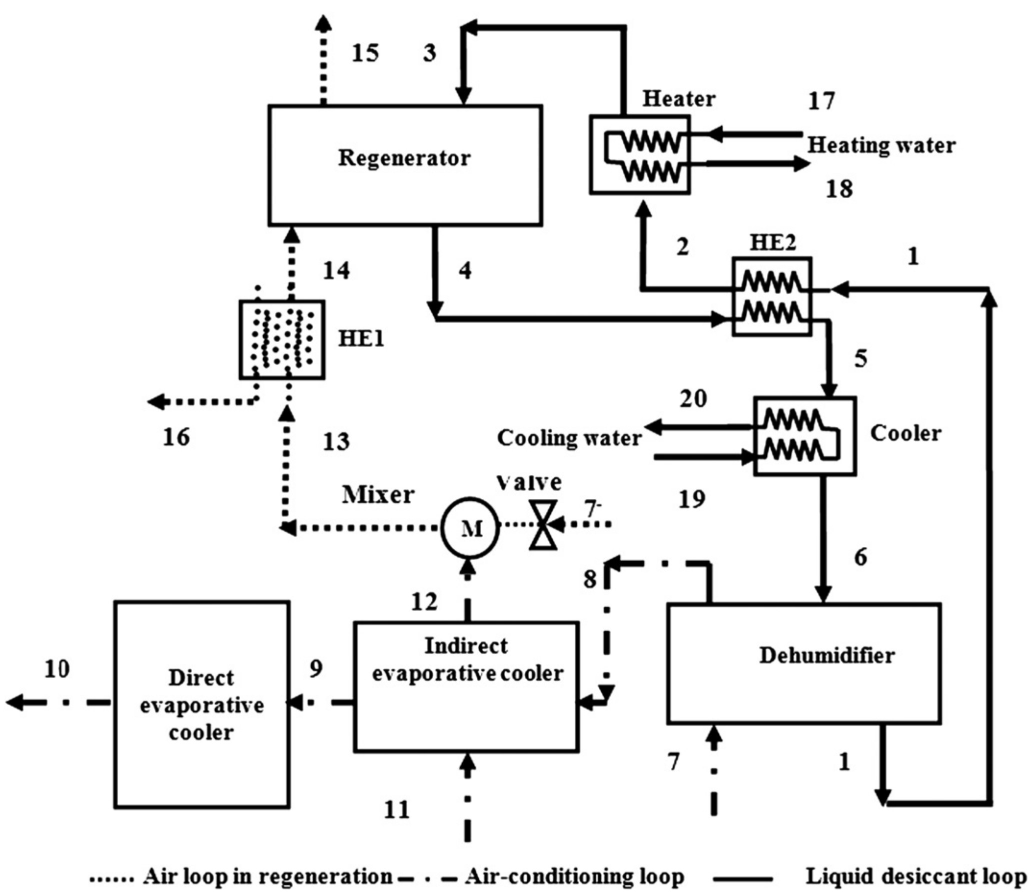

Fig. 23. System schematic of type B configuration [70].

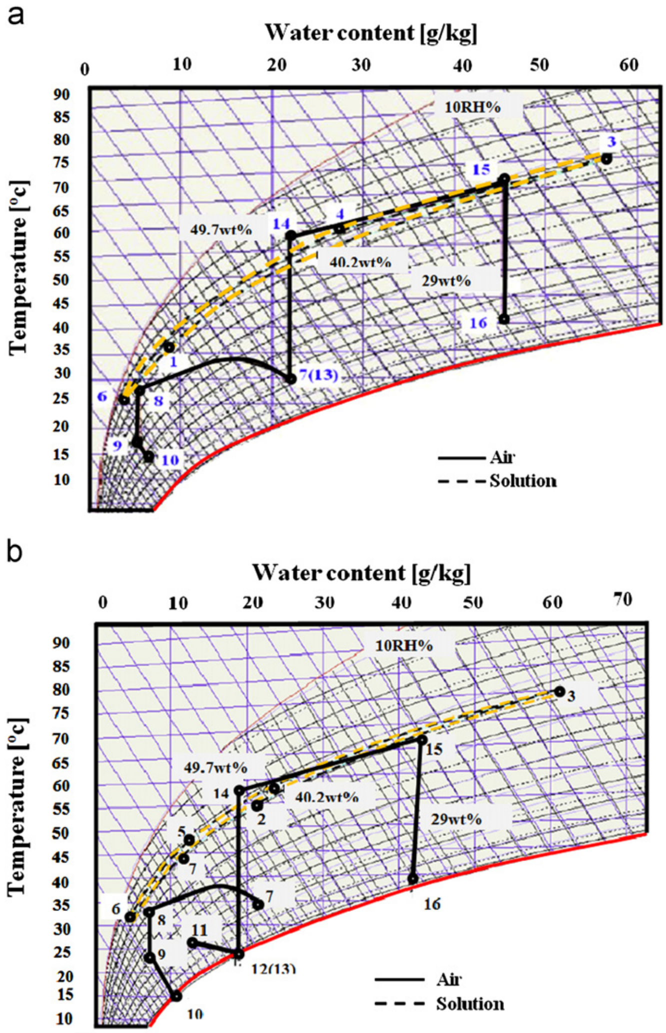

Fig. 24. Simulation results for several important state points of air and solution (a) configuration A and (b) configuration B[69,70].

of the hybrid liquid-desiccant cooling was shown to be better than the vapor-compression system by 23.1–73.8%, and the energy savings were approximately 26–80%, especially when the dehumidification unit and evaporative cooling were used together with the vapor-compression system. On the other hand, the effectiveness of the evaporative cooling unit was reduced because of the high air relative humidity; dehumidifying the air before it is being used in the evaporative cooling unit can improve its effectiveness.

To overcome the limitation capacity of the liquid-desiccant cooling using indirect evaporative cooler, mixing the cooling water with chilled water can bring the water temperature below the ambient wet-bulb temperature; however, this process requires more energy consumption. The combination of evaporative cooling with the liquid-desiccant system is more attractive than either the direct or indirect evaporative cooler.

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